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Spatiotemporal changes in snow cover over China during 1960–2013

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ABSTRACT

Snow cover is highly sensitive to global warming, and it, in return, has huge impacts on global and regional climate change. Because of the limitations of in-situ observations, only a few studies have analyzed the dynamics of snow cover across the whole of China. In this study, we studied the spatio-temporal variabilities of snow cover over China and explored the covary of snow cover with precipitation and temperature in spring and winter based on the surface snow cover observations of 201 meteorological stations in China during 1960–2013. The temporal and spatial distribution characteristics of the mean daily snow depth and the number of snow cover days were analyzed. Results showed snow depth and the number of snow-cover days were high in Northeast China, Eastern China-Inner Mongolia, Northern Xinjiang, Southeastern and South Region of the Tibetan Plateau. The trend of snow depth and the number of snow-cover days varied among different regions. Snow depth recorded at 34.3% of the stations showed an increasing trend during the study period. There were increasing trends of the snow-cover days at 40.8% of stations. Increasing trends of the mean annual daily snow depth and the number of snow-cover days were statistically insignificant ($p > 0.05$) while an abrupt change of the number of snow cover days was found in 1975. Change points of the mean daily snow depth in autumn and winter occurred in 1987 and 2008, respectively. Change points of the number of snow-cover days in spring and winter occurred in 2009 and 1983, respectively. Snow cover in China covaried with various climate factors, i.e., precipitation or temperature. This study improved our knowledge on snow cover changes and is beneficial for further studies on climate change in China.

1. Introduction

Snow on land is a vital component of the global climate system due to its importance for energy and water budget on local and global scales (Groisman et al., 1994). With high reflectance, low thermal conductivity and latent heat of phase changes, snow cover affects surface energy, hydrology, atmospheric circulation and other climate aspects, thus inducing climate change because of global warming (Barnett, 1989; Chen et al., 2016). Thus, snow is one of indicators for climate change analysis. Snow is an important linkage to the radiative balance at high-latitude regions since it is extremely sensitive to changes in air temperature and precipitation (Brown and Goodison, 1996). Therefore, it is of great significance for global climate change studies to monitor and identify changes in snow cover (Ge and Gong, 2009).

During the 1980s–2010s, the global land surface temperature increased at a rate of 0.32 ± 0.09 °C per decade, with the fastest growth occurring in the Northern Hemisphere. At the same time, the area covered by snow has also changed significantly (IPCC, 2007). Since the 1980s, the snow-covered area at high latitudes of the Northern Hemisphere has decreased by about 10% (IPCC, 2007; Dye, 2002). However, there are large spatial variabilities among different places. Snow cover over North America (NA) has increased in the fall half year but decreased in the spring (Brown, 2000). Decreases of winter snowfall were more pronounced in North America (Frei and Robinson, 1999; Laternser and Schneebeli, 2003). Snow cover trends in the mountain regions of Europe were characterized by large regional and altitudinal variations (Scherrer et al., 2004; Brown and Petkova, 2007). Snow cover trends in China showed strong regional variations,Northern Xinjiang, Qinghai-Tibet Plateau and Northeast China, Eastern China-Inner Mongolia, region are the main stable snow cover distribution areas in China (Qin et al., 2006; Zhao and Moore, 2004; Peng et al., 2010). Snow is an important freshwater resource and an important supply for major rivers in China. However, excessive or untimely snow can also cause snow disasters, resulting in heavy losses to the lives and property. Therefore,the snow cover in China has attracted widespread attention.

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Previous studies on snow cover in China mainly were focused on the Qinghai-Tibet Plateau, northern Xinjiang, and northeastern-eastern Inner Mongolia (Xu et al., 2017; Peng et al., 2010; Ma and Qin, 2012). For the Tibetan Plateau, Previous studies were concentrated on the spatial and temporal distribution of snow cover (Qin et al., 2006; Xu et al., 2017; Ding et al., 2008) and the impact of highland snow cover on climate, monsoon, and precipitation over Eurasia (Pu and Xu, 2009; Wang et al., 2018; Khandekar, 1991; Chen and Wu, 2000; Wang et al., 2000; Zhao and Moore, 2004; Wu and Kirtman, 2007; Wu et al., 2009; Zhao et al., 2007). The mean daily snow depth and the number of snow days on the Tibetan Plateau showed an increase trend first (1957–1981/1982) and then a decrease trend (Qin et al., 2006; Xu et al., 2017; Ding et al., 2008). Although snow cover is sensitive to the spatial and temporal variability of regional climate, snow cover also has an important impact on the climate system. The Qinghai-Tibet Plateau is an important snow-covered area in Eurasia and shows an important influence on the weather and climate in China and East Asia. The onset of the summer storm in East Asia is statistically significantly correlated to the winter snow over the Tibetan Plateau (Pu and Xu, 2009; Wang et al., 2018). Changes in the snow cover area, snow cover days, snow depth, and the resulting surface reflectance over the Tibetan Plateau resulted in changes to the general circulation over the nearby regions or even the entire Northern Hemisphere (Khandekar, 1991). Some studies have also found that the snow cover in winter and spring are negatively correlated with precipitation in summer (June–August) in eastern China (Chen and Wu, 2000) and the arid northwestern China in spring (Wang et al., 2000; Wu et al., 2009), while positively correlated with precipitation in summer in the middle and lower stream of the Yangtze River (Wang et al., 2017a; Zhang et al., 2004; Qian et al., 2003) and southern China (Zhao and Moore, 2004; Wu and Kirtman, 2007; Wu et al., 2009; Zhao et al., 2007). Similarly, as one of the regions sensitive to climate change, Xinjiang showed a warming and wetting trend for the past half of a century. The cumulative daily depth of snow cover in the Northern Xinjiang statistically significantly increased from 1961 to 2011 (Qin et al., 2006; Peng et al., 2010), and the snow area exhibited a slightly increasing trend over 2000 to 2012 (Ke and Liu, 2014). The Inner Mongolia-Northeast region is also one of the three most stable snow regions in China. The depth of winter snow cover in Northeastern China increased, while snow depth and snow water equivalent decreased in spring (Ma and Qin, 2012; Peng et al., 2010).

The melting of snow and ice is the main source for regional fresh water supply, and snow cover is also linked to hydrological processes, vegetation phenology, and carbon cycle (Monson et al., 2006; Dorrepaal et al., 2009; Peng et al., 2013). Meanwhile, changes in snow cover have important implications for industrial and agricultural production, transportation, and tourism. It is therefore meaningful to investigate the changes in snow cover over China and their spatio-temporal patterns. Previous studies have mainly investigated snow cover distribution and its variability using satellite-based observations (Zhang et al., 2004; Pu et al., 2007; Ke and Liu, 2014). They have provided much useful information on snow cover changes. However, given the nature of the satellite data, they are not capable of providing snow depth information. Besides, the mean air temperature increased by 0.05 °C to 0.08 °C (Ding et al., 2007), and this warming rate was higher than that of other global regions. Snow cover responses need to be pressingly assessed using secular observations. The length of the satellite data series is usually relatively short, limiting their applications in long-term snow cover change analyses. Based on site observations, the shortcomings of remote sensing data can be effectively overcome, and the long-term monitoring of snow cover variables (including snow depth), can be realized. Therefore, it was necessary to investigate the spatiotemporal pattern of long-term changes in snow cover over China based on measurements collected at gauge stations.

To conclude, this study aimed (*i*) to identify spatial and temporal variability of snow depth and the number of snow-cover days over China, (*ii*) to co-varying relationships between snow depth and other climatic factors (i.e., precipitation and temperature). Based on observed snow data collected at 201 stations across China, we firstly investigated the spatial and temporal variability of snow depth and the number of snow-cover days from 1960 to 2013, then analyzed the abrupt change points of snow cover, finally explored the covary of snow cover with precipitation and temperature in spring and winter.

2. Data and methods

2.1. Snow cover data

Daily snow depth data and meteorological data over the landmass of

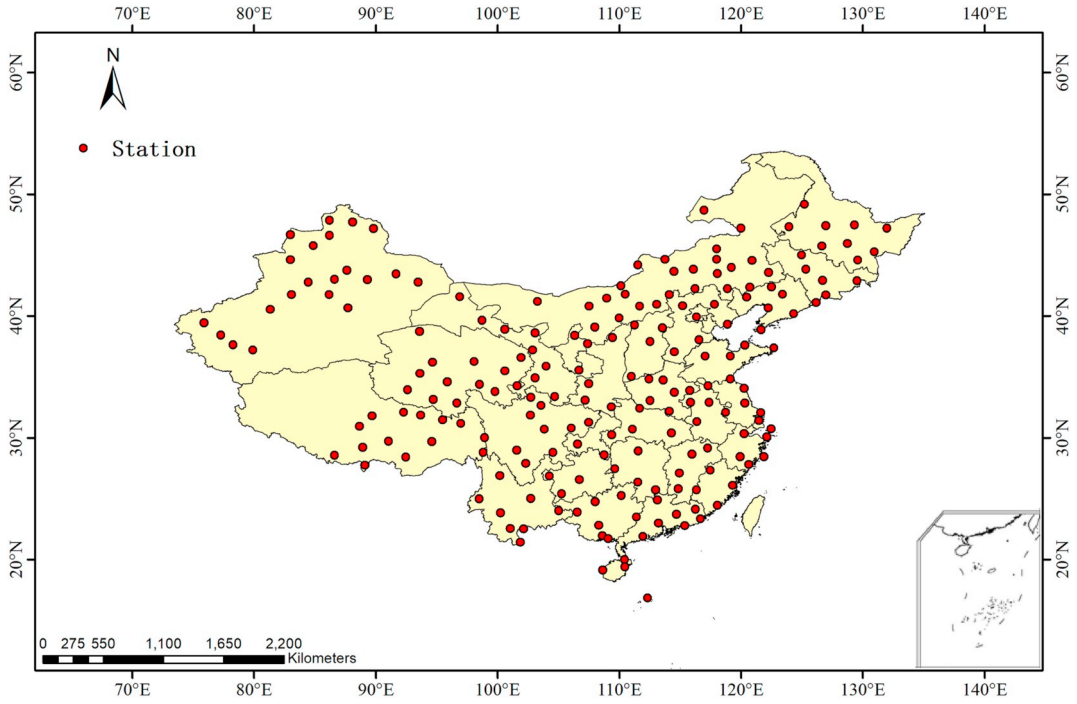

Fig. 1. Distribution of 201 meteorological stations in China.

China were collected from 212 national meteorological stations of the China Meteorological Administration (Fig. 1). This data was validated before it was released. Missing records of daily snow depth data for each site accounted for < 0.2% of the total and had slight effects on the analysis of the whole long time series. Therefore, the missing records were not considered in this study. Different stations have different starting time of observation. Some stations with short observation time period and lack of precise estimate were excluded. Finally, two hundred and one stations with complete observed data from 1960 to 2013 were selected for this study.

The annual snowfall days and snow depth were calculated in the year of a snow year (August 1st to July 31st of the following year). Analyses of seasonal snow changes were based on the four boreal seasons: spring (March–May), summer (June–August), autumn (September–November), and winter (December–February). The mean daily snow depth is the average depth of snow cover in all days over the period analyzed (i.e., spring, summer, autumn, winter, snow cover year). The number of snow days is defined by the standard of snow depth, and the daily snow depth ≥ 0.5 cm is counted as a snow cover day.

2.2. Methods

A linear analysis was used to analyze trends in the mean daily snow depth and the number of snow cover days for each station from 1960 to 2013. We used a linear model $y_t = \beta_1 x_t + \beta_0$ (Xu et al., 2017) to model y_t against time t. In this model, t, β_1 and β_0 are the time, slope and intercept of a regression line, respectively. The statistic $\beta_1/\mathrm{SE}(\beta_1)$ (where $\mathrm{SE}(\beta_1)$ is the standard deviation of β_1) follows Student's t-distribution and Student's t-test was used to identify the statistical significance of a trend and classify a trend to one of groups such as 'weak', 'moderate', or 'strong' trends. Specifically, when $|\beta_1/SE(\beta_1)| < 1.0$, i.e., the absolute value of β_1 is smaller than one standard deviation of the time series tested, the trend is classified as weak; when $1.0 \le |\beta_1/SE(\beta_1)| < t_{0.10}$ where $t_{0.10}$ is the value of Student's t-distribution at the probability of 0.1, the trend is classified as moderate; when $|\beta_1/SE(\beta_1)| \ge t_{0.10}$, the trend is statistically significant and classified as strong. These three categories were further stratified into six categories according to the slope of a trend, i.e., positive weak, positive moderate, positive strong, negative weak, negative moderate, and negative strong (Table 1).

The ordered clustering method can reflect the variance of time series, so it was used to test abrupt change points. A time series is divided to the early and later periods. When the sum of the variances of the two periods is smallest, this point is the abrupt change point.

Let the possible mutation point be τ, then the sum of the squared residuals of the early and later periods can be calculated as:

$$V_\tau = \sum_{i=1}^{\tau} (x_i - \bar{x}_\tau)^2 \quad (1)$$

$$V_{n-\tau} = \sum_{i=\tau+1}^{\tau} (x_i - \bar{x}_{n-\tau})^2 \quad (2)$$

where $\bar{x}_\tau x_\tau$, $\bar{x}_{n-\tau}$e the mean of the early and later periods. The sum of the squared residuals can be expressed as:

$$S_n(\tau) = V_\tau + V_{n-\tau} \quad (3)$$

When $S = \min\{S_n(\tau)\}$ $(2 \le \tau \le n\text{-}1)$, τ is the optimal two-partition point and can be inferred as the most probable mutation point. After inferring the mutation point τ, the significance of the possible mutation point is tested by a rank sum test.

$$U = \frac{W - \left(\frac{n_1 + n_2 + 1}{2}\right)}{\sqrt{\frac{n_1 n_2 (n_1 + n_2 + 1)}{12}}} \quad (4)$$

where n_1, n_2 are the sample size of the early and later periods, respectively. When the absolute value of the test statistic is greater than $|U_{0.05}| = 1.96$, then the mutation point is statistically significant, otherwise it is not significant. The time series was divided into two periods with significant mutation points and then a piecewise linear regression was used to analyze the trend changes of snow cover variables before and after the abrupt change.

Snowfall occurs mostly in spring and winter. Temperature changes in spring and winter can affect the ablation of snow. Changes in precipitation also directly affect the depth of snow cover. We further analyzed covary of snow cover with precipitation and temperature in spring and winter. Due to limits of observed weather data, stations without observed daily snowfall were removed and 162 stations were finally selected. According to different climate types, China is divided into five climatic zones, i.e., tropical monsoon, subtropical monsoon, temperate monsoon, temperate continental, and alpine plateau. The correlations of precipitation, temperature, mean daily snow depth and the number of snow cover days on 162 stations in different climate zones were analyzed.

Table 1
Classification of trend.

Categories	Condition
Negative Weak	$-1.0 < \beta_1/SE(\beta_1) < 0$
Negative Moderate	$-t_{0.10} < \beta_1/SE(\beta_1) \le -1.0$
Negative Strong	$\beta_1/SE(\beta_1) \le -t_{0.10}$
Positive Weak	$0 < \beta_1/SE(\beta_1) < 1.0$
Positive Moderate	$1.0 \le \beta_1/SE(\beta_1) < t_{0.10}$
Positive Strong	$\beta_1/SE(\beta_1) \ge t_{0.10}$

3. Results

3.1. Spatial variability of snow cover

The mean daily snow depth and the number of snow cover days in spring, summer, autumn, and winter from 1960 to 2013 are shown in Fig. 2a-d and Fig. 2f-i. The spatial pattern of mean daily snow depth and the number of snow cover days are considerably different in the four seasons. The mean daily snow depth and the number of snow cover days in spring were similar in western China, southern China and North China. However, in Central China, Northeast China, northern Xinjiang and Qinghai-Tibet Plateau, and East China, the mean daily snow depth and the number of snow cover days varied greatly. There was snow cover in the middle of the Tibetan plateau, eastern and central Inner Mongolia. Autumn mean daily snow depth and the number of snow cover days were more consistent in spatial distribution across the country than those in other seasons. Regions with high values of mean daily snow depth and the number of snow cover days were located in the northeast and the east of Inner Mongolia, the north of Xinjiang and the Qinghai-Tibet Plateau, and East China. There was no snow cover in the south of China in summer. In winter, regions with high values of mean daily snow depth were located in the northeast and east of Inner Mongolia, the north of Xinjiang, the middle and east of the Qinghai-Xizang Plateau and North China, while regions with high values of the number of snow cover days were only located in the northeast and the east of Inner Mongolia, and the north of Xinjiang.

The spatial pattern of the number of snow cover days and the snow depth were marginally the same (Fig. 2e and j). Nationally, the snow depth showed high values in the three regions. They are (*i*) northern Xinjiang (the north of the Tianshan Mountains) where the largest value ($10.30\ \mathrm{cm\ day^{-1}}$) of mean daily snow depth occurred in Altay, (*ii*) the northeast and east of Inner Mongolia where the average annual mean daily snow depth of Nenjiang County amounted to $3.81\ \mathrm{cm\ day^{-1}}$, (*iii*) the south of the Tibetan Plateau and the north of the Himalayas where

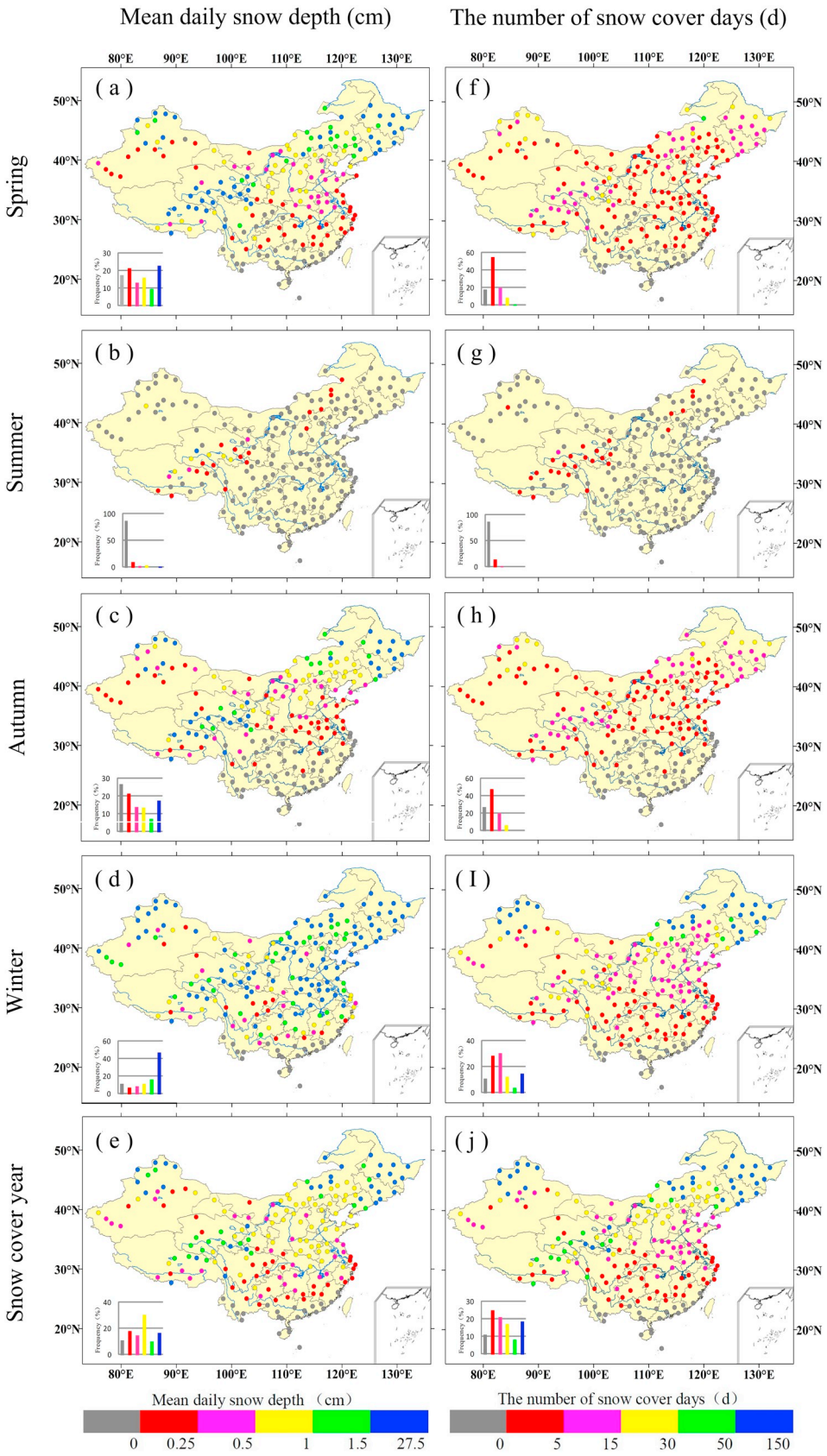

Fig. 2. Spatial patterns of mean daily snow depth and the number of snow-cover days across 201 stations during 1960–2013 (The numbers shown in figures are based on snow levels.)

the maximum annual average snow depth (2.47 cm day^{-1}) occurred in Parry. The three regions of high-value of annual snow cover days were located in (*i*) the Northeast China and the east of Inner Mongolia with a maximum annual snow-cover days of 149 days year $^{-1}$, (*ii*) the north of the Tianshan Mountains, (*ii*) the south of the Altai Mountains with a maximum annual snow-cover days of 133 days year $^{-1}$, and (*iii*) the Qinghai-Tibet Plateau with the highest value occurring in Sanjiangyuan area. Due to the high altitude, low temperature and long time period of snow accumulation, the water source region for the three largest rivers (i.e., Yangtze River, Huanghe River, and Mekong River) showed the maximum annual snow-cover days (66 days year^{-1}), although the snowfall amount over this region was relatively low (Fig. 2e).

The spatial distribution of the mean daily snow depth and snow cover days in the spring, summer, autumn, and winter of 1960–2013 is shown in Fig. 2a-d and Fig. 2f-i. There were large seasonal differences in the spatial distribution between the mean daily snow depth and the number of snow-cover days. The number of stations with mean daily snow depth in spring, summer, and autumn being < 0.5 cm, accounted for 51.74%, 96.52%, and 62.19% of the total number of stations, respectively. The stations with mean daily snow depth > 1.5 cm in winter account for 63.18% of the total number of stations and mainly located in the area north of the Yangtze River. The number of stations of snow-cover days in spring, summer and autumn < 5 days accounted for 72.14%, 99.50% and 74.63% of the total number of stations, respectively. There were more stations of snow-cover days in winter > 5 days, accounting for 60.70% of the total number of stations, mainly distributed in the north of the Qinling-Huaihe River Basin.

3.2. Temporal variability of snow cover

Changes in the mean daily snow depth and the number of snow cover days and their spatial distribution were shown in Fig. 3e and j. The mean daily snow depth showed an increase over regions including the Northeast China, Lesser Khingan Mountains and Greater Khingan Mountains, northern Xinjiang, southeastern Yunnan-Guizhou plateau, and the lower reaches of the Yangtze River. The number of snow cover days increased over regions including the central and west of Northeast China and East Inner Mongolia, northern Xinjiang, and northeastern Qinghai-Tibet Plateau (Southern Qinghai Province), the east of the Yunnan-Guizhou Plateau. Regions of growing snow cover days were more widespread than those of the growing annual mean daily snow depth. There was a decrease in the number of snow cover days and snow depth in many stations scattered across the entire country (Fig. 3e and j).

The comparison of snow depth and snow-cover days (Fig. 3e and j) shows that both changes over the same regions were consistent. Snow depth and the number of snow-cover days increased steadily in regions over the Northeast China, the east of Inner Mongolia, northern Xinjiang, and eastern Yunnan-Guizhou Plateau. Stations with strong trends in the mean snow depth in spring, summer, autumn and winter accounted for 5.97%, 6.97%, 11.94% and 13.43% of the total number of stations, respectively. There were 10.94%, 8.96%, 5.47%, and 12.44% of stations showing strong trends in the number of snow-cover days in spring, summer, autumn and winter, respectively. Although there were differences in the trend between the daily mean snow depth and snow-cover days, there was a spatial consistency between the mean daily snow depth and the number of snow-cover days in terms of the overall increases or decreases. The mean daily snow depth on 38.31% of stations in spring showed an increase, mainly distributed in Northeast China, central and eastern Inner Mongolia, northern Xinjiang, eastern Qinghai-Tibet Plateau and some regions over the middle and downstream of the Yangtze River (including Hubei Province, northern Jiangxi Province and Zhejiang Province). Among these regions, the increases on seven stations including Nenjiang, Aershan, and Fujin were strong. There were 39.80% of stations showing an increase in the number of snow-cover days, mainly over central and northern regions of Northeastern China, central and eastern regions of Inner Mongolia, northern and western Xinjiang, southern and northeastern Qinghai-Tibet Plateau, and the downstream of the Yangtze River (including northern Jiangxi Province, central and southern Anhui Province, and northern Jiangsu Province). There were strong increases on 12 stations including Nenjiang, Xinbaerhuyouqi and Aershan (Fig. 3a and f). In winter, the mean daily snow depth on 41.79% of stations increased. These stations are mainly located in Northeast China and eastern Inner Mongolia, northern Xinjiang, eastern Tibetan plateau, and eastern and central Yunnan-Guizhou Plateau. The increase of the mean daily snow depth on 25 stations such as Nenjiang, Xinbaerhuyouqi and Aershan were strong. There were 46.27% of stations showing increasing snow-cover days, among which 21 stations including Xinbaerhuyouqi, Aershan and Qiqihar showed strong increases in the mean daily snow depth (Fig. 3d and i). These stations were located in the same regions as those for the mean daily snow depth, in addition to Hebei Province and Northern Shandong Province.

3.3. Abrupt changes of snow cover

During 1960–2013, the mean annual daily snow depth in China was 0.93 cm, which increased by 0.028 cm per decade, but the increase was not statistically significant (R^2 = 0.0649, p = 0.063). The mean annual snow-cover days was 25.13 days and increased by 0.49 day per decade, but the increase was not statistically significant (R^2 = 0.0411, p = 0.142) (Fig. 4).

The mean daily snow depth abruptly changed in autumn and winter. There were also abrupt changes in the number of snow days in spring and winter (Fig. 5). The mean daily snow cover depth in autumn and winter showed an abrupt change in 1987 and 2008 (U = −2.082 and U = 2.16) (Figs. 5). The variability and trends before and after the change point were shown in Fig. 6a-b and 6c-d. The mean daily snow depth in autumn increased (decreased) before (after) the change point in some stations over the south of the North China Plain and the north of the Northeast Plain. Thus, these stations showed abrupt changes from increases to decreases. Some stations in the Northeast Plain showed abrupt changes from decreases to increases (Fig. 6a-b). 48.76% (40.80%) of stations showed an increase in the mean snow depth in winter during 1960–2008 (2008–2013) (Fig. 6c-d). Some stations in the Northern Xinjiang, northeastern Qinghai-Tibet Plateau, the Hetao Plain, and the central and eastern regions of the Yunnan-Guizhou Plateau show abrupt changes in the mean snow depth from an increase to a decrease.

Trends of snow-cover days in each season were not statistically significant. Statistically significant abrupt change points in spring and winter of snow-cover days occurred in 2009 and 1983 (U = 2.54 and U = 2.49) (Fig. 5). After an abrupt change, the number of stations showing an increase in spring snow-cover days decrease by 20.90%. There is no spring snowfall in the south of the Yangtze River Basin. The snow-cover days in the Huaihe River Basin showed both increase and decrease while the snow-cover days in northern Xinjiang drastically decreased (Fig. 6e-f). The number of stations showing an increase in winter snow-cover days decreased from 51.24% to 40.30% after the change point. Most stations in Northeast China shifted from decreasing trends to increasing trends in 1983. In eastern and southeast Qinghai-Xizang Plateau, the south of Qinling and Huaihe River, the north of Yangtze River Basin and northern regions of Zhejiang and Fujian hilly areas, the days of snow cover increased before abrupt change points and then decreased after that. In the Altai area, Xinjiang, the trend of snow cover days shifted from an increase to a decrease (Fig. 6g-h).

The annual snow cover days shifted statistically significantly in 1975 (U = 2.06) (Fig. 5). The number of the stations showing an increase in snow-cover days decreased by 9.95% after 1975. Seventy-eight percent of stations in the south of Qinling-Huaihe area and some stations in the Qinghai-Tibet Plateau showed an increase-to-decrease abrupt change. The number of snow days in central Northeast China

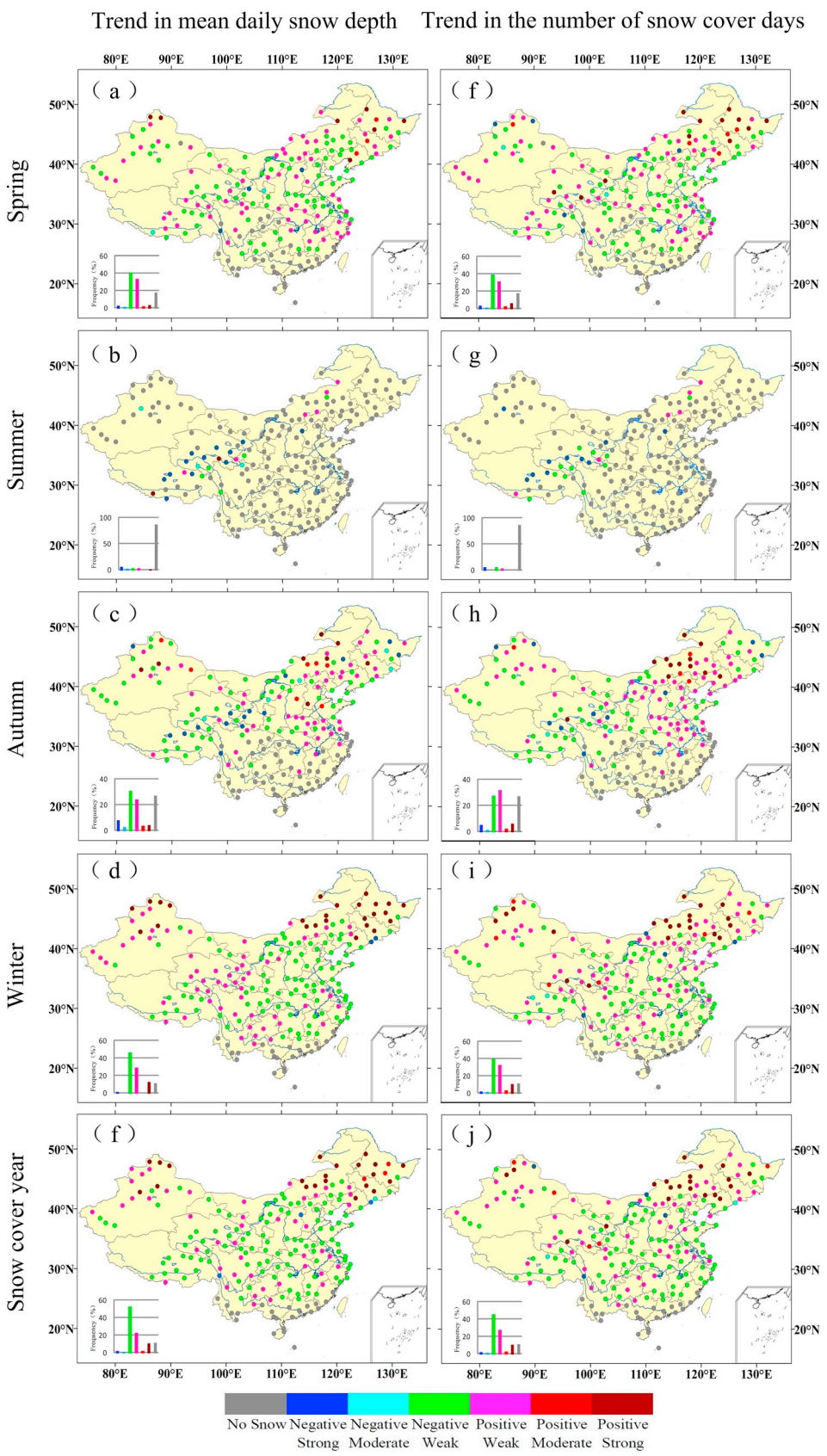

Fig. 3. Trends in mean daily snow depth and the number of snow-cover days across 201 stations during 1960–2013.

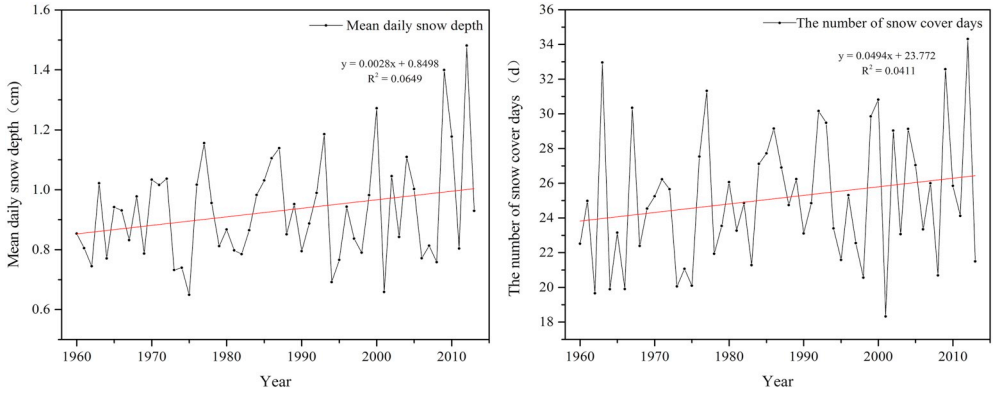
Mean daily snow depth
y = 0.0028x + 0.8498
R² = 0.0649
Mean daily snow depth (cm)
Year
The number of snow cover days
y = 0.0494x + 23.772
R² = 0.0411
The number of snow cover days (d)
Year

Fig. 4. Variations of mean daily snow depth and the number of snow-cover days in China during 1960–2013.

and northern Xinjiang showed a trend shift from a decrease to an increase (Fig. 6i-j).

3.4. Covary of snow cover with temperature and precipitation

During 1960–2013, precipitation in spring and winter in all climatic zones showed an increase trend, except that the spring rainfall in subtropical monsoon climatic regions showed a decrease trend. The increase rates ranged from 0.24 to 1.72 mm per decade (Fig. 7). Winter precipitation in the subtropical monsoon climate zone increased the most while winter precipitation in the temperate continental climate zone increased the least among the five climatic zones. Spring and winter temperature over the four climatic zones showed an increase (0.24–0.44 °C per decade). Winter temperature in the alpine plateau climate zone increased the most and winter temperature increased least in the subtropical monsoon climate zone among the five climatic zones.

Basically, no correlation was identified between snow cover and temperature and precipitation in spring (Table 2) while precipitation highly covaried with the number of snow cover days and mean daily snow depth changes in winter. For example, from 1960 to 2013, the number of snow cover days and the mean daily snow depth in spring decreased in the alpine plateau climate zone, which coincided with changes in the surface air temperature (Fig. 7 and Table 2). In spring, the number of snow cover days and the mean daily snow depth in the alpine plateau climate zone were statistically significantly, negatively correlated with surface air temperature. The snow days in the temperate continental climate zone were statistically significantly, negatively correlated with precipitation. In winter, the number of snow cover days in the high mountain climate zone, the temperate continental climate zone, and the temperate monsoon climate zone all showed statistically significant, positive correlation with precipitation (Fig. 7). The number of snow cover days in the temperate monsoon climate zone was statistically significantly, negatively correlated with temperature. The number of snow cover days and the mean snow depth in the subtropical monsoon climate zone are all statistically significantly, negatively correlated with temperature.

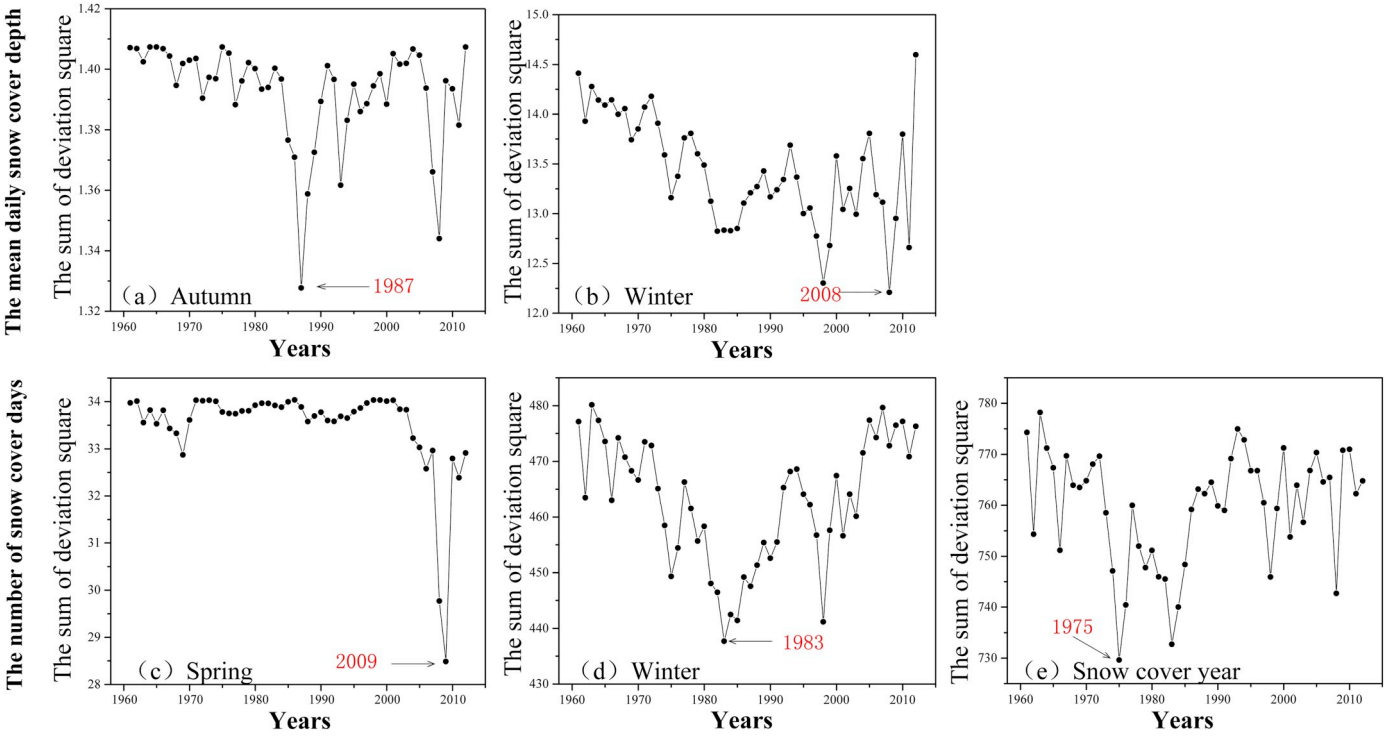

Fig. 5. The variation process of the sum of deviation square of mean daily snow depth and the number of snow-cover days during 1960–2013.

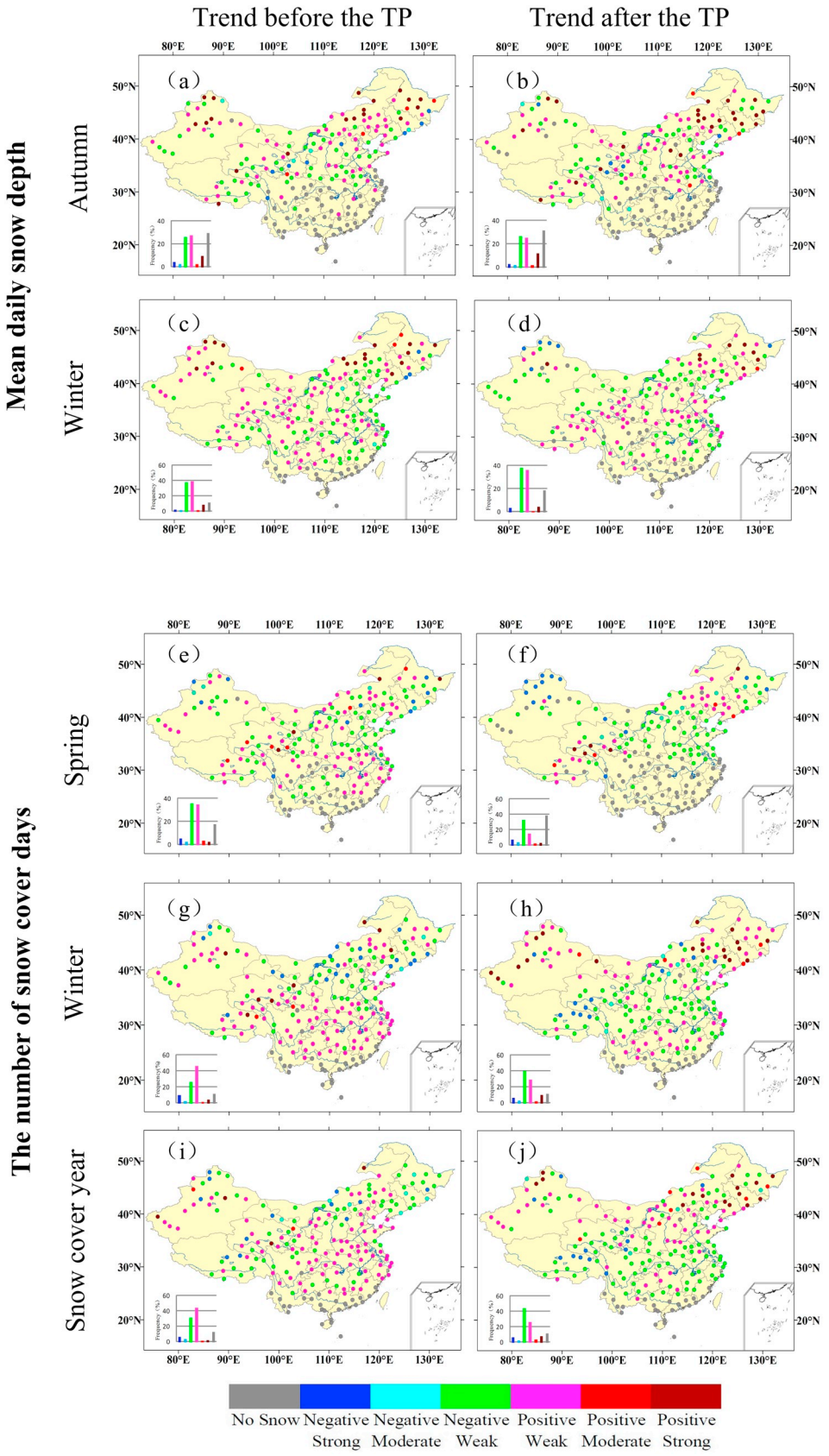

Fig. 6. The trend (left) before and (right) after the TP, the inset graphs at bottom left show the frequency distributions of corresponding trends.

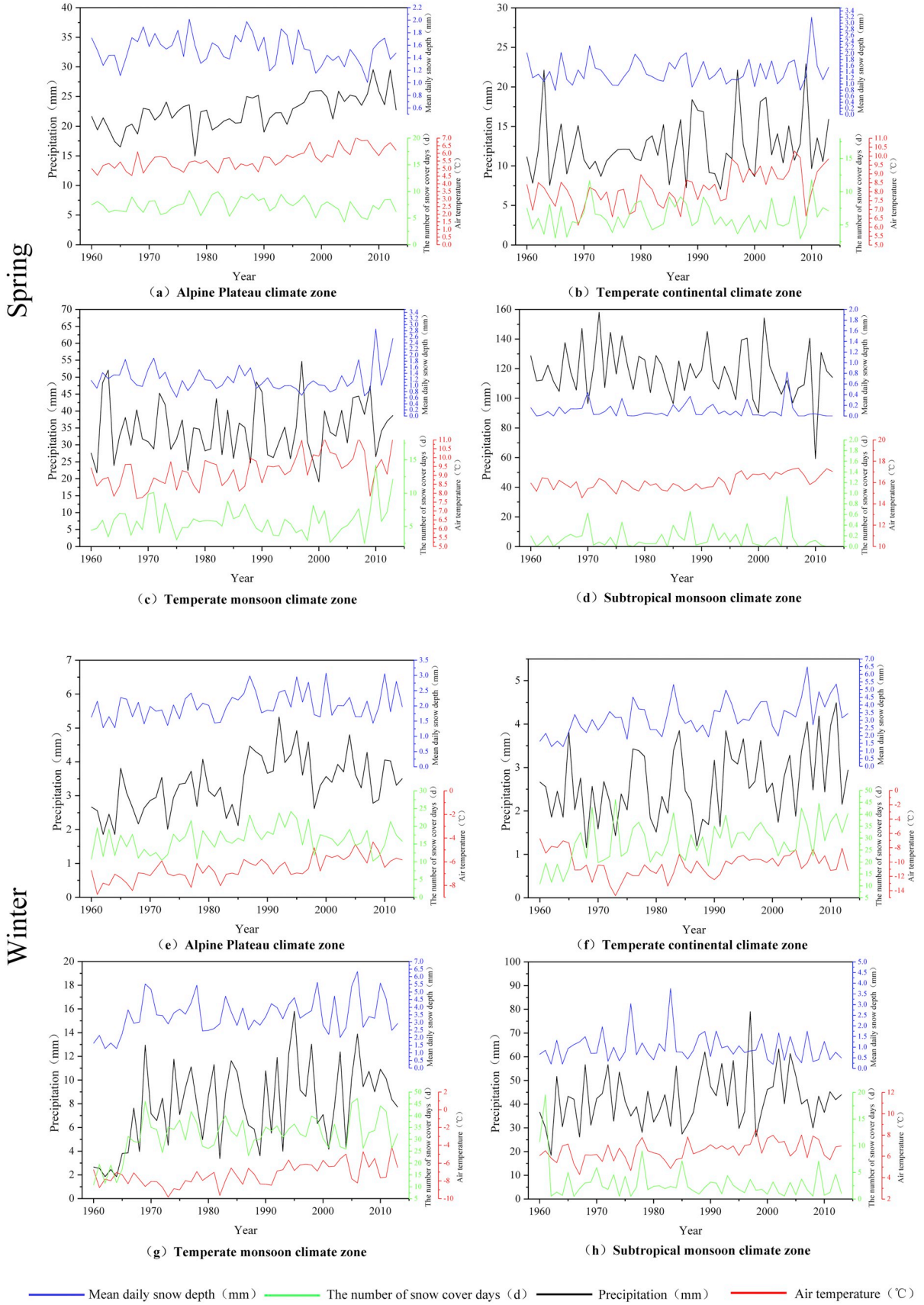

Fig. 7. Interannual variability of precipitation (black line), air temperature (red line), mean daily snow depth (blue line), and the number of snow-cover days (green line) in spring during the period of 1960–2013. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 2
Correlation between mean snow depth, the number of snow cover days, air temperature and precipitation in different climatic zones.

		Alpine Plateau climate zone		Temperate continental climate zone		Temperate monsoon climate zone		Subtropical monsoon climate zone	
		The number of snow cover days	Mean daily snow depth	The number of snow cover days	Mean daily snow depth	The number of snow cover days	Mean daily snow depth	The number of snow cover days	Mean daily snow depth
Spring	Precipitation	−0.073	−0.082	−0.29*	−0.17	−0.048	−0.027	0.0057	0.0094
	Temperature	−0.29*	−0.30*	0.073	0.075	−0.0056	0.030	−0.039	0.0022
Winter	Precipitation	0.68**	0.58**	0.53**	0.75**	0.50**	0.42**	0.029	0.035
	Temperature	−0.22	0.078	−0.25	−0.075	−0.37**	−0.25	−0.61**	−0.53**

* significant at $P \leq 0.05$.
** significant at $P \leq 0.01$.

4. Discussion

The results showed that there are evident spatial differences in snow cover in China. Northeast China. Eastern China-Inner Mongolia, Northern Xinjiang, Central and Eastern Region of the Tibetan Plateau are the three regions of high values of snow depth and the number of snow-cover days. This is consistent with the research results of Wang et al. (2009). The annual mean daily snow depth in most regions of Northeast China, Lesser Khingan Range and Greater Khingan Mountains regions, northern Xinjiang, southeastern Yunnan-Guizhou Plateau and the downstream of the Yangtze River Basin shows an increasing trend. The increasing area of the number of snow cover days occurred in the central and western part of Northeast China and the east of Inner Mongolia, the north of Xinjiang, the northeast of Tibetan Plateau, and the east of Yunnan-Guizhou Plateau. This is consistent with the analysis results for some specific regions of China, e.g., Tibetan Plateau (Che et al., 2008; Ma and Qin, 2012), the north of Xinjiang (Ma and Qin, 2012; Peng et al., 2010; Qin et al., 2006), and Northeast China (Peng et al., 2010). However, Previous study found that winter snow depth showed a decreasing trend in the Yunnan-Guizhou Plateau (Peng et al., 2010). There was no significant correlation among snow cover and temperature and precipitation in spring, except in alpine plateau climate zones (Table 2). But precipitation was found to be highly covaried with the number of snow cover days and mean daily snow depth changes in winter. In winter, the number of snow cover days in the temperate continental climate zone showed statistically significant positive correlation with precipitation. Our finding is not consistent with that of Qin et al. (2006), where no correlation was found between snow cover and precipitation in the Northwest China. Such difference may be explained by the unconformity length of time series. Meanwhile, the discrepancy in the selected sites and analytical methods will also have an impact on the results of the analysis. The results showed that the spatial variability of mean daily snow depth and the number of snow cover days in China did not change statistically significantly under the background of global warming.

Temperature and precipitation in China all showed an increase with rates around 0.05 °C to 0.08 °C per decade and 0.3% to 0.4% per decade in the 20th century, respectively (Ding et al., 2007). Resulted from increasing anthropogenic greenhouse gas emissions, the warming has been accelerated in recent decades. Changes in snow cover are closely related to the influencing factors such as external forcings and atmospheric circulation system. Previous studies show that Arctic Oscillations (AO), Siberian High, East Asian winter monsoon, and Pacific and Atlantic sea surface temperatures (SST), Arctic sea ice showed important effects on variability of snow cover in China (Bamzai, 2003; Yeo et al., 2017; Gong et al., 2001; Wu and Wang, 2002; Wang and Chen, 2010; Shaman and Tziperman, 2005; Yang, 1996; Li and Wang, 2013). AO and atmospheric circulation affects the snow cover by influencing the spatiotemporal variability of snowfall and temperature. Many studies have pointed out that the AO in winter is most significantly associated with snow cover in winter and spring in China (Bamzai, 2003; Yeo et al., 2017). The AO and Siberian high are inversely related. The influence of AO on precipitation is more significant than Siberian high, but the effect of Siberian high on air temperature is more significant than AO in China (Gong et al., 2001; Wu and Wang, 2002). The East Asian winter monsoon anomaly has a great correlation with rainfall and temperature in China. In strong winter monsoon years, there is less precipitation and lower temperature in most part of China (Wang and Chen, 2010). El Nino Southern Oscillation (ENSO) as the most obvious signal of the interannual variation of SST has a significant impact on snow cover in China through the adjustment of circulation and Atmospheric quasi-static Rossby wave train (Shaman and Tziperman, 2005). The warming climate and the increases of the Arctic temperature led to frequent extreme weather and abnormal climate in the mid-latitude region, mainly manifested by the increase of severe weather in Eurasia, the increase of snowfall and snow cover in winter in mid-latitudes, and the increase of snow cover in northern and central China (Yang, 1996; Li and Wang, 2013).

Changes in snowfall over China are consistent with changes in precipitation and temperature. In the north of Xinjiang, the central and east of the Tibetan Plateau, the northeast, and the central and east of Inner Mongolia, the snow cover is widespread. These regions are located at high latitudes or high altitudes with low temperatures and low rainfall. The amount of snow, precipitation and temperature in these regions all showed a statistically significant increase, which is also found by some previous studies (e.g., Wang et al., 2012; Ding et al., 2007; Zhou et al., 2018; Bai et al., 2007; Wang et al., 2017b). However, the snowfall in the above region is not concentrated in every year, even though the days of snowfall in these regions are more than those in other regions (Zhou et al., 2018), thus resulting in three regions of high values of snow cover and the increasing land area with snow cover over China (Figs. 2 and 3). The annual precipitation in south-central Northeast China, North China, Central China and the Loess Plateau is decreasing (Bai et al., 2007; Liu et al., 2005) with the increasing temperature (Cui et al., 2017). The number of snow cover days and mean

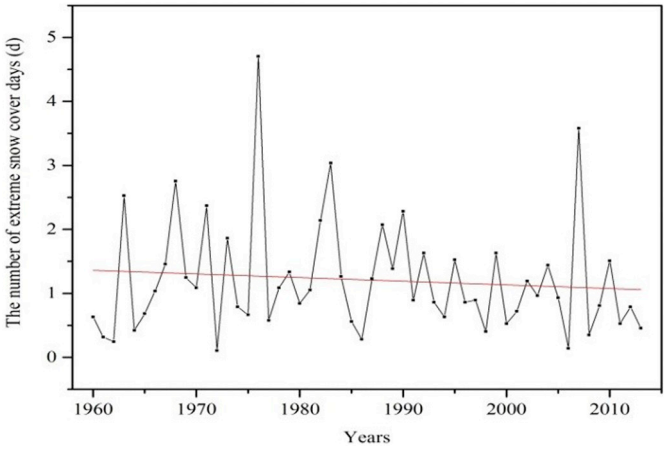

Fig. 8. The average annual extreme snow days in subtropical monsoon climate.

daily snow depth are decreasing (Fig. 3e and j). In South China, the number of days with extremely deep snow cover accounts for a large proportion of the total number of snow cover days (Zhou et al., 2018). However, the increasing temperature was not conducive to the occurrence of snow cover. As a result, the number of snow cover days showed a decreasing trend (Fig. 3j). The annual mean number of days with extremely deep snow cover showed no statistically significant decreases (Fig. 8), although there were high values in the 1970s and the 2000s. The probability of extreme weather events will increase greatly in the future (Tan et al., 2018), and the variation of snow cover needs further research.

5. Conclusions

In this study, we investigated the spatial and temporal variability of mean daily snow depth and the number of snow-cover days and explored the covary of snow cover with precipitation and temperature in spring and winter over China from 1960 to 2013. There are three regions in China with high values of the mean daily snow cover depth and the number of snow cover days. They are the northeast and east of Inner Mongolia, northern Xinjiang, and the middle and east of Tibetan Plateau. The Altay region in the north of Xinjiang shows the largest annual mean daily snow cover depth in China, while the largest annual number of snow cover days occurred in the Alshan region in Northeast China. The annual mean daily snow depth in Northeast China, Lesser Khingan Mountains and Greater Khingan Mountains regions, northern Xinjiang, the southeastern Yunnan-Guizhou Plateau and the downstream of the Yangtze River Basin showed an increasing trend. There were some regions showing increasing snow accumulation, such as the central east and the west of Northeast China, eastern Mongolia, northern Xinjiang, northeast Tibetan Plateau, and eastern Yunnan-Guizhou Plateau. During 1960–2013, there were no abrupt changes in the mean daily snow depth in the whole country, but the abrupt change in the number of snow cover days occurred in 1975. The mean daily snow depth in autumn and winter shifted statistically significantly in 1987 and 2008, respectively. Statistically significant abrupt changes in the number of snow cover days in spring and winter occurred in 2009 and 1983, respectively. Snow cover in China covaried with various climate factors, i.e., precipitation or temperature.

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References

Bai, A., Zhai, P., Liu, X., 2007. Climatology and trends of wet spells in China. Theor. Appl. Climatol. 88, 139–148.
Bamzai, A.S., 2003. Relationship between snow cover variability and Arctic Oscillation index on a hierarchy of time scales. Int. J. Climatol. 23, 131–142.
Barnett, T.P., 1989. The effect of Eurasian snow-cover on regional and global climate variations. J. Atmos. Sci. 46, 661–686.
Brown, R.D., 2000. Northern Hemisphere snow cover variability and change, 1915–97. J. Clim. 13, 2339–2355.
Brown, R.D., Goodison, B.E., 1996. Interannual variability in reconstructed Canadian snow cover, 1915–1992. J. Clim. 9, 1299–1318.
Brown, R.D., Petkova, N., 2007. Snow cover variability in Bulgarian mountainous regions, 1931–2000. Int. J. Climatol. 27, 1215–1229.
Che, T., Xin, L., Jin, R., Armstrong, R., Zhang, T., 2008. Snow depth derived from passive microwave remote-sensing data in China. Ann. Glaciol. 49, 145–154.
Chen, L., Wu, R., 2000. Interannual and decadal variations of snow cover over Qinghai-Xizang Plateau and their relationships to summer monsoon rainfall in China. Adv. Atmos. Sci. 17, 18–30.
Chen, X., Liang, S., Cao, Y., He, T., 2016. Distribution, attribution, and radiative forcing of snow cover changes over China from 1982 to 2013. Clim. Chang. 137, 363–377.
Cui, L.L., Shi, J., Du, H.Q., Wen, K.M., 2017. Characteristics and trends of climatic extremes in China during 1959-2014. J. Trop. Meteorol. 23, 368–379.
Ding, Y., Ren, G., Zhao, Z., Xu, Y., Luo, Y., Li, Q., Zhang, J., 2007. Detection, causes and projection of climate change over China: an overview of recent progress. Adv. Atmos. Sci. 24, 954–971.
Ding, Y., Wang, Z., Sun, Y., 2008. Inter-decadal variation of the summer precipitation in East China and its association with decreasing Asian summer monsoon. Part i: observed evidences. Int. J. Climatol. 28, 1139–1161.
Dorrepaal, E., Toet, S., Logtestijn, R.S.P.V., Swart, E., Weg, M.J.V.D., Callaghan, T.V., et al., 2009. Carbon respiration from subsurface peat accelerated by climate warming in the subarctic. Nature 460, 616–619.
Dye, D.G., 2002. Variability and trends in the annual snow-cover cycle in Northern Hemisphere land areas, 1972–2000. Hydrol. Process. 16, 3065–3077.
Frei, A., Robinson, D.A., 1999. Northern Hemisphere snow extent: regional variability 1972–1994. Int. J. Climatol. 19, 1535–1560.
Ge, Y., Gong, G.V., 2009. North American snow depth and climate teleconnection patterns. J. Clim. 22, 217–233.
Gong, D.Y., Wang, S.W., Zhu, J.H., 2001. East Asian winter monsoon and arctic oscillation. Geophys. Res. Lett. 28, 2073–2076.
Groisman, P.Y., Karl, T.R., Knight, R.W., Stenchikov, G.L., 1994. Changes of snow cover, temperature, and radiative heat balance over the Northern Hemisphere. J. Clim. 7, 1633–1656.
IPCC (Intergovernmental Panel on Climate Change), 2007. Climate Change 2007: The Physical Science Basis. Cambridge University Press, Cambridge.
Ke, C., Liu, X., 2014. MODIS-observed spatial and temporal variation in snow cover in Xinjiang, China. Clim. Res. 59, 15–26.
Khandekar, M.L., 1991. Eurasian snow cover, Indian monsoon and El Niño/Southern Oscillation – a synthesis. Atmosphere. 29, 636–647.
Laternser, M., Schneebeli, M., 2003. Long-term snow climate trends of the Swiss Alps (1931–99). Int. J. Climatol. 23, 733–750.
Li, F., Wang, H., 2013. Autumn Sea Ice Cover, Winter Northern Hemisphere Annular Mode, and Winter Precipitation in Eurasia. J. Clim. 26, 3968–3981.
Liu, B., Xu, M., Henderson, M., Qi, Y., 2005. Observed trends of precipitation amount, frequency, and intensity in China, 1960–2000. J. Geophys. Res. Atmos. 110, D08103.
Ma, L.J., Qin, D.H., 2012. Temporal-spatial characteristics of observed key parameters of snow cover in China during 1957–2009. Sci. Cold Arid Regions 4, 384 (in Chinese).
Monson, R.K., Lipson, D.L., Burns, S.P., Turnipseed, A.A., Delany, A.C., Williams, M.W., Schmidt, S.K., 2006. Winter forest soil respiration controlled by climate and microbial community composition. Nature 439, 711–714.
Peng, S., Shilong, P., Philippe, C., Fang, J., Wang, X., 2010. Change in winter snow depth and its impacts on vegetation in China. Glob. Chang. Biol. 16, 3004–3013.
Peng, S., Piao, S., Ciais, P., Friedlingstein, P., Zhou, L., Wang, T., 2013. Change in snow phenology and its potential feedback to temperature in the Northern Hemisphere over the last three decades. Environ. Res. Lett. 8, 1880–1885.
Pu, Z., Xu, L., 2009. MODIS/Terra observed snow cover over the Tibet Plateau: distribution, variation and possible connection with the East Asian summer monsoon (EASM). Theor. Appl. Climatol. 97, 265–278.
Pu, Z., Xu, L., Salomonson, V.V., 2007. MODIS/Terra observed seasonal variations of snow cover over the Tibetan Plateau. Geophys. Res. Lett. 34, 137–161.
Qian, Y.F., Zheng, Y.Q., Zhang, Y., Miao, M.Q., 2003. Responses of China's summer monsoon climate to snow anomaly over the Tibetan Plateau. Int. J. Climatol. 23, 593–613.
Qin, D., Liu, S., Li, P., 2006. Snow cover distribution, variability, and response to climate change in western China. J. Clim. 19, 1820–1833.
Scherrer, S.C., Appenzeller, C., Laternser, M., 2004. Trends in Swiss alpine snow days: the role of local- and large-scale climate variability. Geophys. Res. Lett. 31, L13215.
Shaman, J., Tziperman, E., 2005. The effect of Enso on Tibetan Plateau snow depth: a stationary wave teleconnection mechanism and implications for the South Asian monsoons. J. Clim. 18, 2067–2079.
Tan, X., Gan, T.Y., Horton, D.E., 2018. Projected timing of perceivable changes in climate extremes for terrestrial and marine ecosystems. Glob. Chang. Biol. 24, 4696–4708.
Wang, L., Chen, W., 2010. How well do existing indices measure the strength of the East Asian winter monsoon? Adv. Atmos. Sci. 27, 855–870.
Wang, C.H., Dong, A.X., Yang, D.B., Wang, S.G., 2000. The correlation between precipitation in Northwest China during spring and snow depth in the Tibetan Plateau. J. Glaciol. Geocryol. 22, 340–346 (in Chinese).
Wang, C.H., Wang, Z.L., Cui, Y., 2009. Snow cover of China during the last 40 years: spatial distribution and interannual variation. J. Glaciol. Geocryol. 31, 301–310 (in Chinese).
Wang, H.J., Sun, J.Q., Chen, H.P., Zhu, Y.L., Zhang, Y., Jiang, D.B., Yang, S., 2012. Extreme climate in China: Facts, simulation and projection. Meteorol. Z. 21, 279–304.
Wang, C., Yang, K., Li, Y., Wu, D., Bo, Y., 2017a. Impacts of spatiotemporal anomalies of Tibetan Plateau snow cover on summer precipitation in East China. J. Clim. 30, 885–903.
Wang, Y., Zhou, B., Qin, D., Jia, W.U., Gao, R., Song, L., 2017b. Changes in mean and extreme temperature and precipitation over the arid region of Northwestern China: observation and projection. Adv. Atmos. Sci. 34, 289–305.
Wang, Z., Wu, R., Chen, S., Huang, G., Liu, G., Zhu, L., 2018. Influence of western Tibetan Plateau summer snow cover on East Asian summer rainfall. J. Geophys. Res. Atmos. 123, 2371–2386.
Wu, R., Kirtman, B.P., 2007. Observed relationship of spring and summer East Asian rainfall with winter and spring Eurasian snow. J. Clim. 20, 1285–1304.
Wu, B., Wang, J., 2002. Winter Arctic Oscillation, Siberian high and East Asian winter monsoon. Geophys. Res. Lett. 29, 1–3.
Wu, B.Y., Yang, K., Zhang, R., 2009. Eurasian snow cover variability and its association with summer rainfall in China. Adv. Atmos. Sci. 26, 31–44.
Xu, W., Ma, L., Ma, M., Zhang, H., Yuan, W., 2017. Spatial-Temporal variability of snow cover and depth in the Qinghai-Tibetan Plateau. J. Clim. 30, 1521–1533.

Yang, S., 1996. ENSO–snow–monsoon associations and seasonal–interannual predictions. Int. J. Climatol. 16, 125–134.
Yeo, S.R., Kim, W.M., Kim, K.Y., 2017. Eurasian snow cover variability in relation to warming trend and Arctic Oscillation. Clim. Dyn. 48, 499–511.
Zhang, Y., Li, T., Wang, B., 2004. Decadal change of the spring snow depth over the Tibetan Plateau: the associated circulation and influence on the East Asian summer monsoon. J. Clim. 17, 2780–2793.
Zhao, H., Moore, G.W.K., 2004. On the relationship between Tibetan snow cover, the Tibetan Plateau monsoon and the Indian summer monsoon. Geophys. Res. Lett. 31, 101–111.
Zhao, P., Zhou, Z., Liu, J., 2007. Variability of Tibetan spring snow and its associations with the hemispheric extratropical circulation and East Asian summer monsoon rainfall: an observational investigation. J. Clim. 20, 3942–3955.
Zhou, B., Wang, Z., Shi, Y., Ying, X.U., Han, Z., 2018. Historical and future changes of snowfall events in China under a warming background. J. Clim. 31, 5873–5889.